UNIVERSITÄT ZU LÜBECK
INSTITUTE OF SOFTWARE ENGINEERING
AND PROGRAMMING LANGUAGES

isp

Runtime Verification with Predictive Semantics

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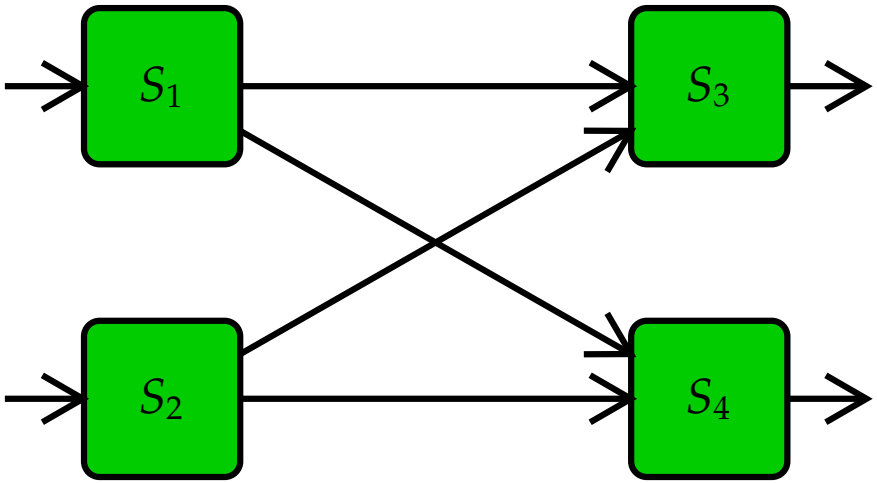
Norfolk, April 2012

Runtime Verification (RV)



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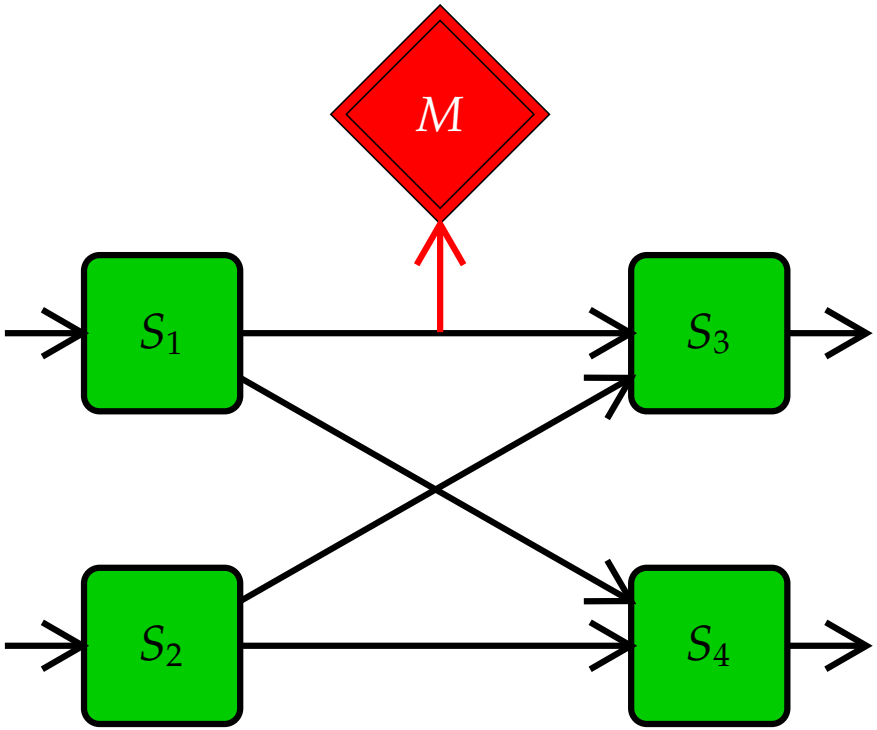
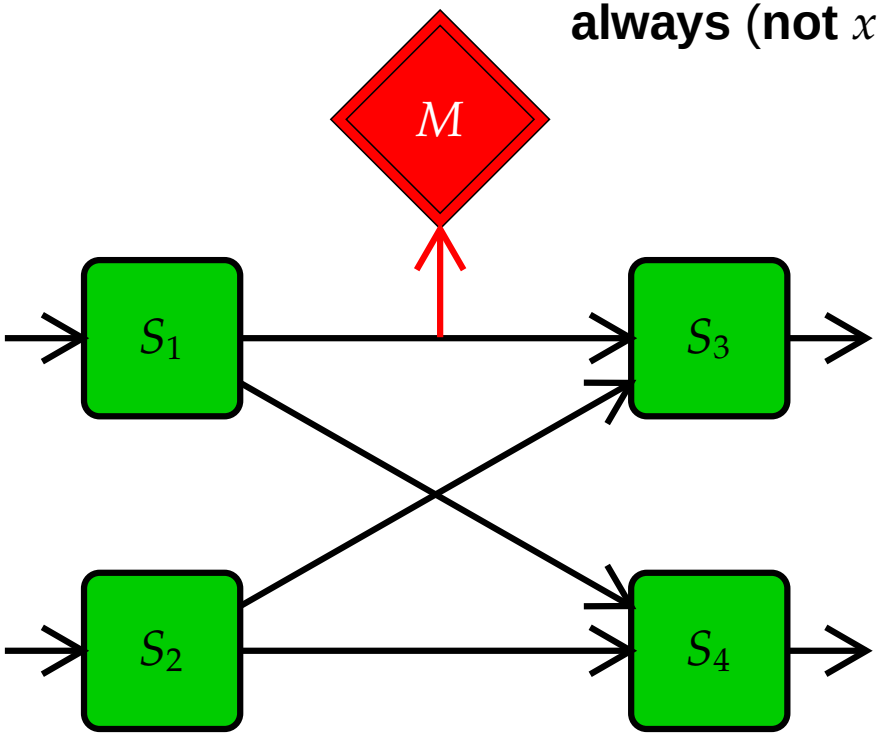


Runtime Verification (RV)

always (not $x > 0$ **implies next** $x > 0$**)**



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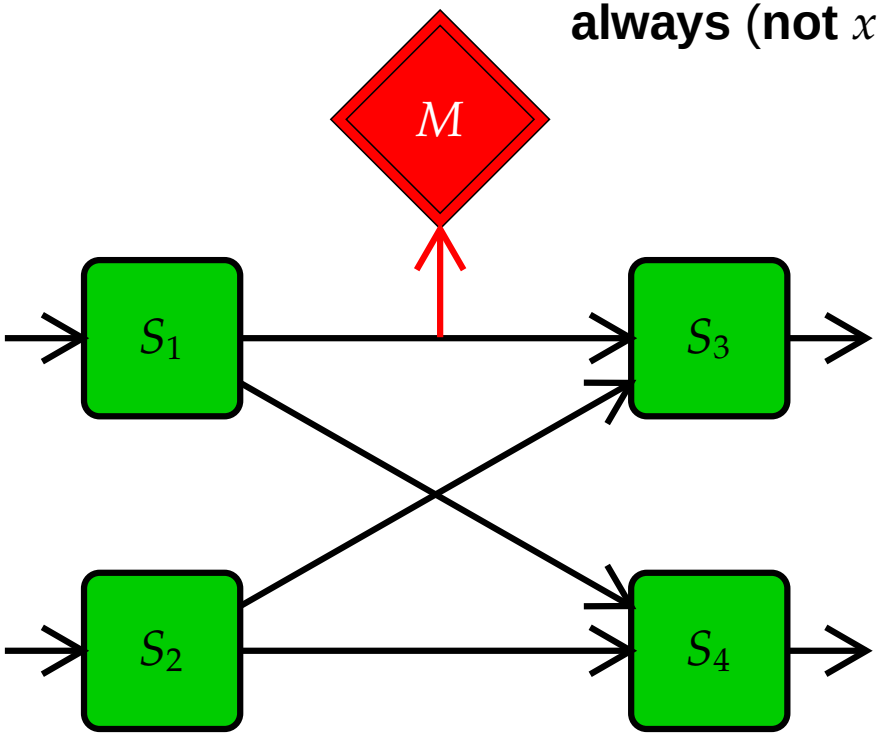

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- Verifies (partially) correctness properties based on actual executions

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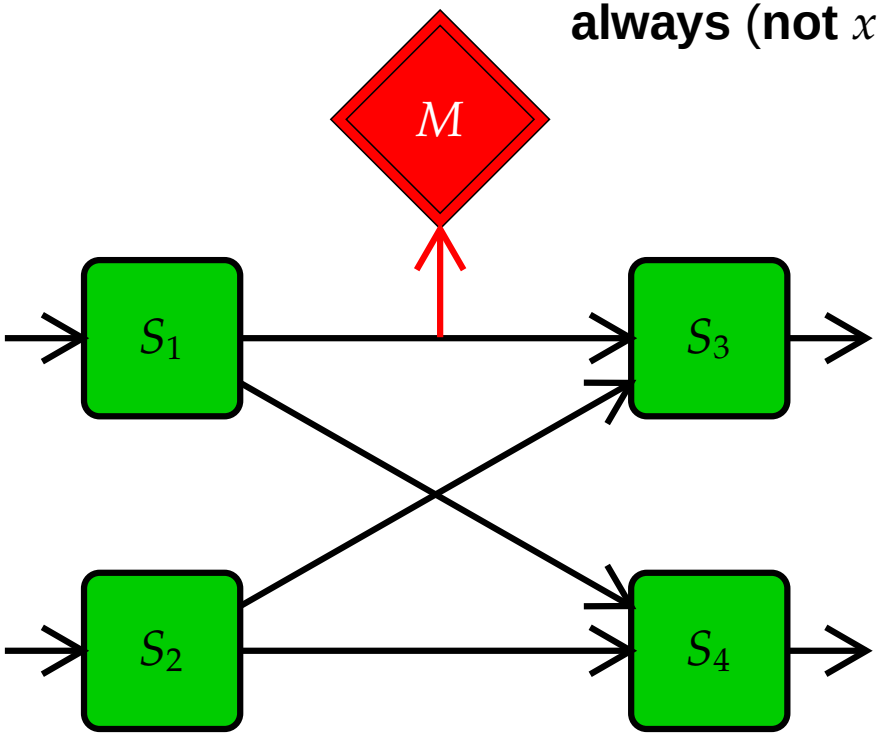

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- Verifies (partially) correctness properties based on actual executions
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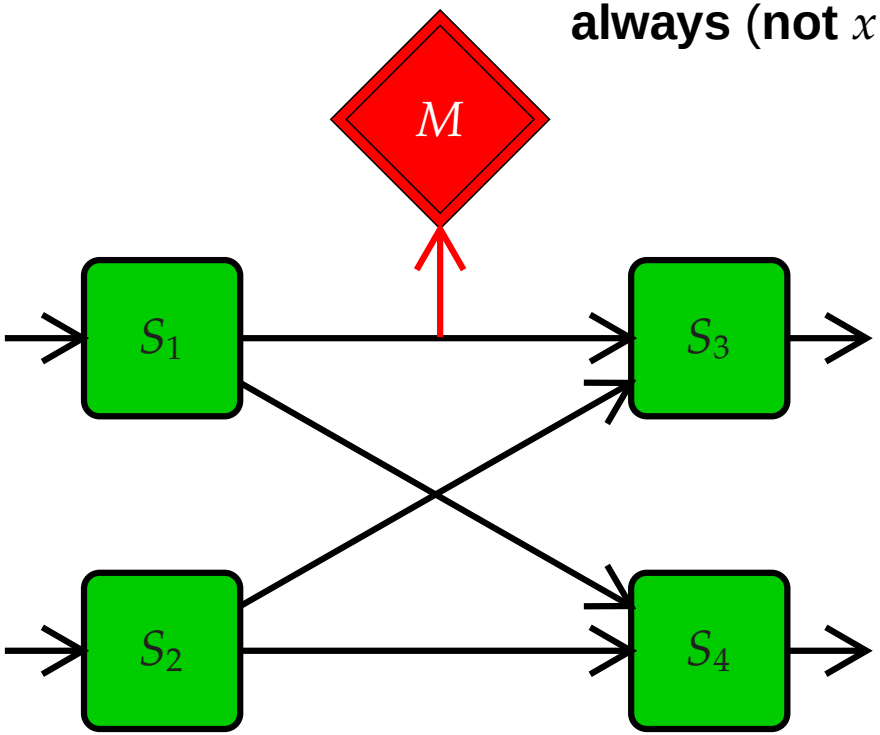

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- Complementing

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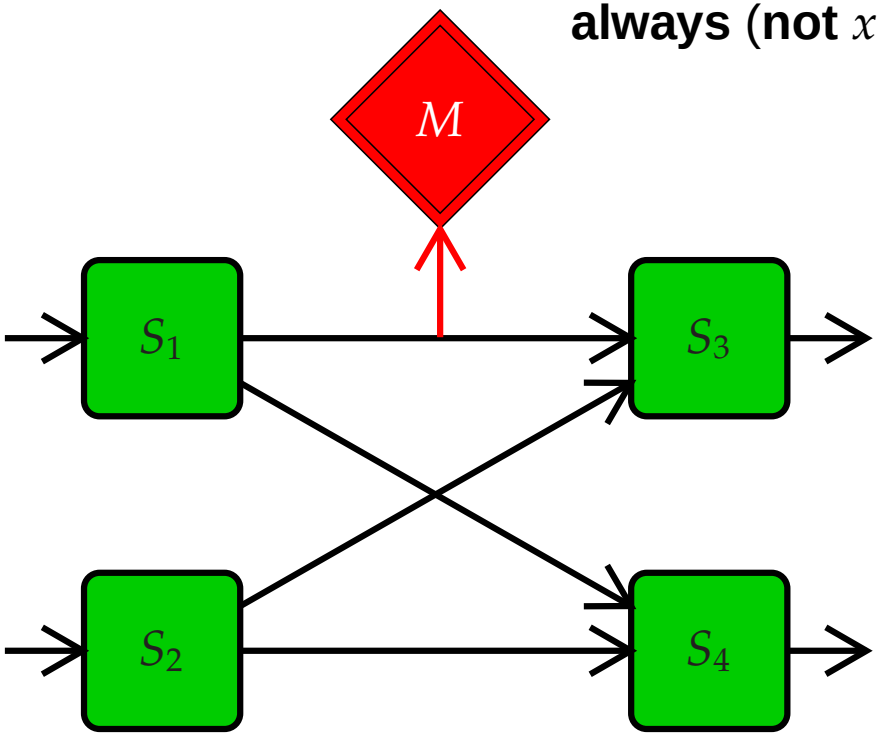

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- Verifies (partially) correctness properties based on actual executions
- Simple verification technique
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  - Model Checking

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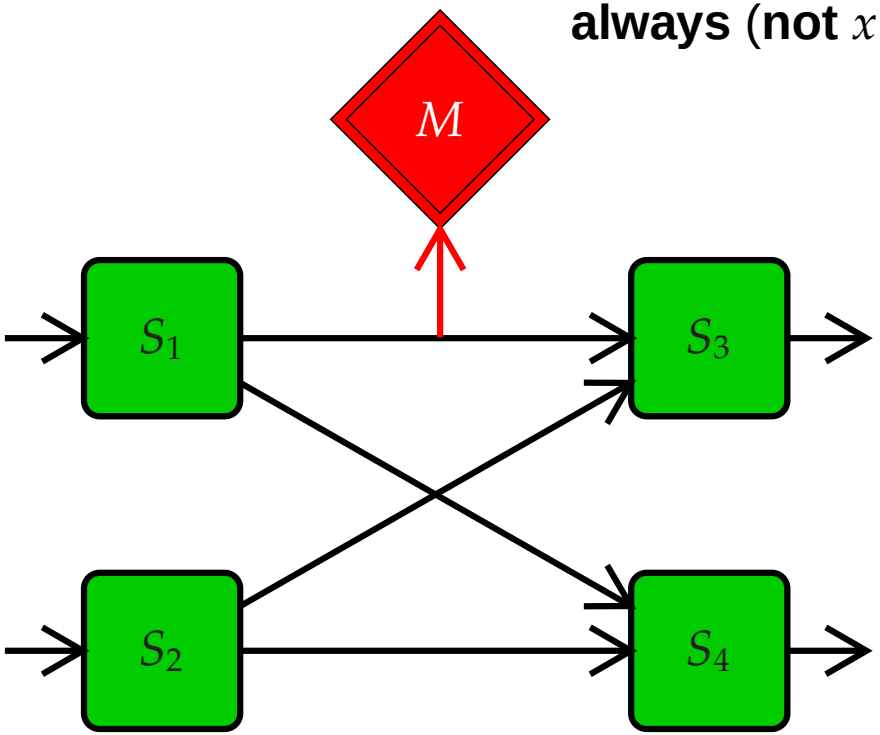

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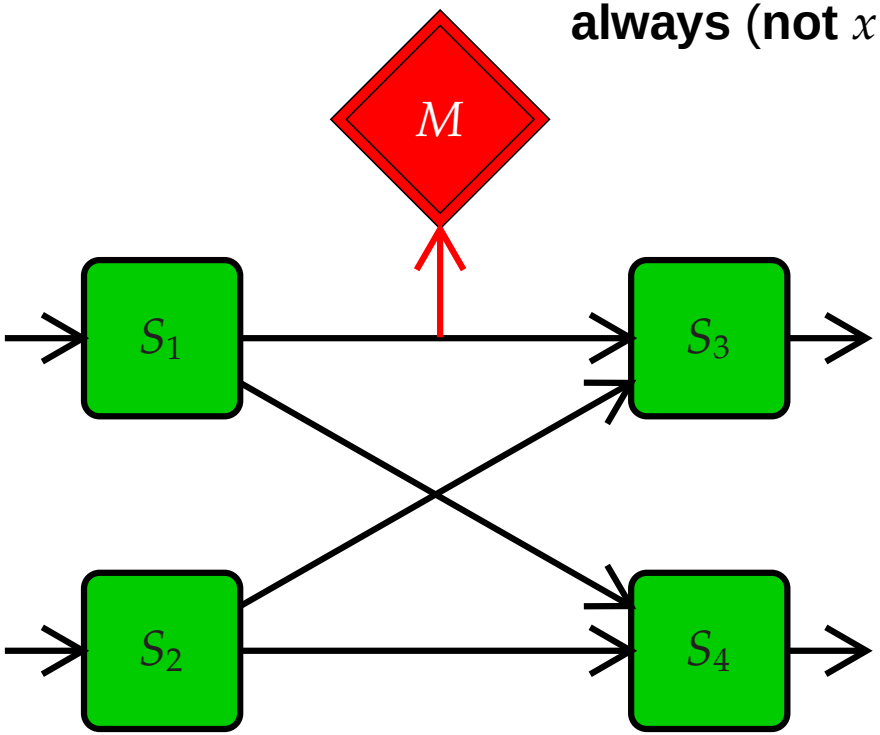


Characterisation

- Verifies (partially) correctness properties based on actual executions
- Simple verification technique
- Complementing
  - Model Checking
  - Testing
- Formal: $w \in \mathcal{L}(\varphi)$

Outline

Presentation outline

Runtime Verification for LTL

Observing executions/runs

Runtime Verification for LTL

Observing executions/runs

Idea

Specify correctness properties in LTL

Runtime Verification for LTL

Definition (Syntax of LTL formulae)

Let p be an atomic proposition from a finite set of atomic propositions AP. The set of LTL formulae, denoted with LTL, is inductively defined by the following grammar:

$$\begin{aligned} \varphi \quad ::= \quad & \mathit{true} \mid p \mid \varphi \vee \varphi \mid \varphi \, U \, \varphi \mid X\varphi \mid \\ & \mathit{false} \mid \neg p \mid \varphi \wedge \varphi \mid \varphi \, R \, \varphi \mid \bar{X}\varphi \mid \\ & \neg\varphi \end{aligned}$$

Truth Domains

Lattice

- A lattice is a partially ordered set $(\mathcal{L}, \sqsubseteq)$ where for each $x, y \in \mathcal{L}$, there exists
  1. a unique greatest lower bound (glb), which is called the meet of x and y, and is denoted with $x \sqcap y$, and
  2. a unique least upper bound (lub), which is called the join of x and y, and is denoted with $x \sqcup y$.
- A lattice is called finite iff $\mathcal{L}$ is finite.
- Every finite lattice has a well-defined unique least element, called bottom, denoted with $\bot$,
- and analogously a greatest element, called top, denoted with $\top$.

Truth Domains (cont.)

Lattice (cont.)

- A lattice is distributive, iff $x \sqcap (y \sqcup z) = (x \sqcap y) \sqcup (x \sqcap z)$, and, dually, $x \sqcup (y \sqcap z) = (x \sqcup y) \sqcap (x \sqcup z)$.
- In a de Morgan lattice, every element x has a unique dual element $\overline{x}$, such that $\overline{\overline{x}} = x$ and $x \sqsubseteq y$ implies $\overline{y} \sqsubseteq \overline{x}$.

Definition (Truth domain)

We call $\mathcal{L}$ a truth domain, if it is a finite de Morgan lattice.

LTL's semantics using truth domains

Definition (LTL semantics (common part))

Semantics of LTL formulae over a finite or infinite word $w = a_0 a_1 \ldots \in \Sigma^\infty$

Boolean constants

$$[w \models \mathit{true}]_{\mathfrak{L}} = \top \qquad [w \models \mathit{false}]_{\mathfrak{L}} = \bot$$

Boolean combinations

$$[w \models \neg\varphi]_{\mathfrak{L}} = \overline{[w \models \varphi]_{\mathfrak{L}}}$$
$$[w \models \varphi \vee \psi]_{\mathfrak{L}} = [w \models \varphi]_{\mathfrak{L}} \sqcup [w \models \psi]_{\mathfrak{L}}$$
$$[w \models \varphi \wedge \psi]_{\mathfrak{L}} = [w \models \varphi]_{\mathfrak{L}} \sqcap [w \models \psi]_{\mathfrak{L}}$$

atomic propositions

$$[w \models p]_{\mathfrak{L}} = \begin{cases} \top & \text{if } p \in a_0 \\ \bot & \text{if } p \notin a_0 \end{cases} \qquad [w \models \neg p]_{\mathfrak{L}} = \begin{cases} \top & \text{if } p \notin a_0 \\ \bot & \text{if } p \in a_0 \end{cases}$$

next X/weak next X TBD

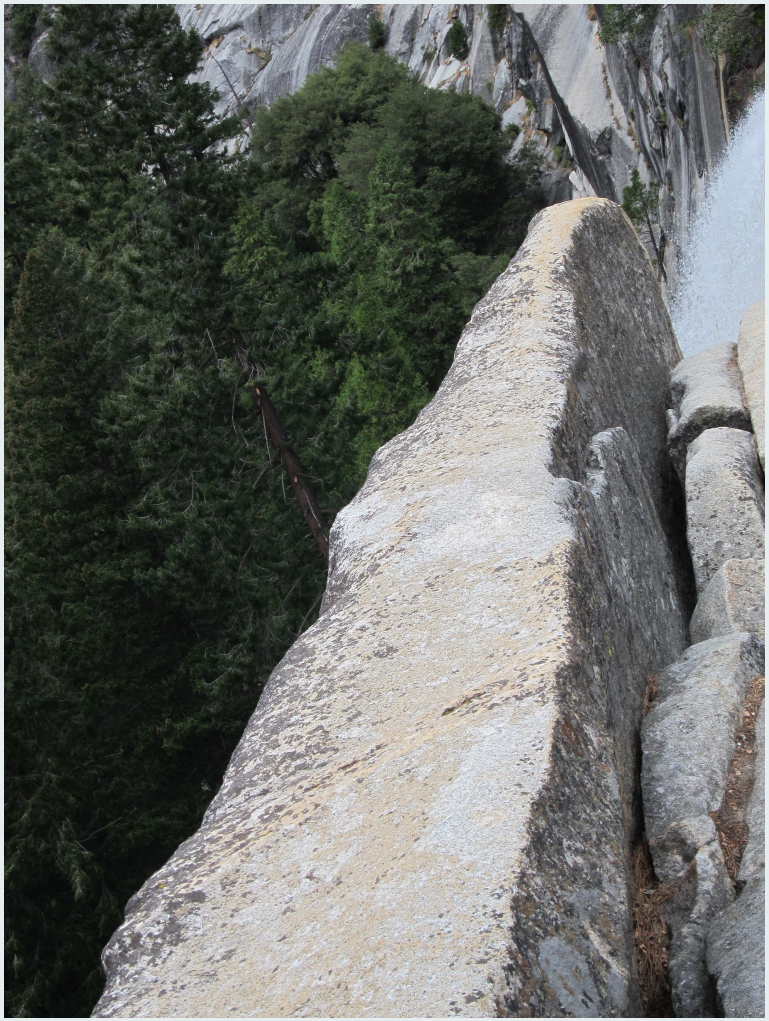
until/release

$$[w \models \varphi \; U \; \psi]_{\mathfrak{L}} = \begin{cases} \top & \text{there is a } k,\ 0 \le k < |w| : [w^k \models \psi]_{\mathfrak{L}} = \top \text{ and} \\ & \text{for all } l \text{ with } 0 \le l < k : [w^l \models \varphi] = \top \\ \mathit{TBD} & \text{else} \end{cases}$$

$$\varphi \; R \; \psi \equiv \neg(\neg\varphi \; U \; \neg\psi)$$

LTL on finite words

Application area: Specify properties of finite word



LTL on finite words

Definition (FLTL)

Semantics of FLTL formulae over a word $u = a_0 \dots a_{n-1} \in \Sigma^*$

next

$$[u \models X\varphi]_F = \begin{cases} [u^1 \models \varphi]_F & \text{if } u^1 \neq \epsilon \\ \bot & \text{otherwise} \end{cases}$$

weak next

$$[u \models \bar{X}\varphi]_F = \begin{cases} [u^1 \models \varphi]_F & \text{if } u^1 \neq \epsilon \\ \top & \text{otherwise} \end{cases}$$

LTL on finite, but not completed words

Application area: Specify properties of finite but expanding word

LTL on finite, but not completed words

Be Impartial!

- go for a final verdict ($\top$ or $\bot$) only if you really know

LTL on finite, but not complete words

Impartiality implies multiple values

Every two-valued logic is not impartial.

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Semantics of FLTL formulae over a word $u = a_0 \dots a_{n-1} \in \Sigma^*$

next

$$[u \models X\varphi]_F = \begin{cases} [u^1 \models \varphi]_F & \text{if } u^1 \neq \epsilon \\ \bot^p & \text{otherwise} \end{cases}$$

weak next

$$[u \models \bar{X}\varphi]_F = \begin{cases} [u^1 \models \varphi]_F & \text{if } u^1 \neq \epsilon \\ \top^p & \text{otherwise} \end{cases}$$

Anticipatory Semantics

Consider possible extensions of the non-completed word

LTL for RV [BLS@FSTTCS'06]

Basic idea

- LTL over infinite words is commonly used for specifying correctness properties
- finite words in RV:
  prefixes of infinite, so-far unknown words
- re-use existing semantics

LTL for RV [BLS@FSTTCS'06]

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3-valued semantics for LTL over finite words

$$[u \models \varphi] = \begin{cases} \top & \text{if } \forall \sigma \in \Sigma^\omega : u\sigma \models \varphi \\ \bot & \text{if } \forall \sigma \in \Sigma^\omega : u\sigma \not\models \varphi \\ ? & \text{else} \end{cases}$$

Impartial Anticipation

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- Stay with $\top$ and $\bot$

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Anticipatory

- Go for $\top$ or $\bot$
- Consider $XXXfalse$

$$\epsilon \quad \models \quad XXXfalse$$

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$$\epsilon \models XXXfalse$$
$$a \models XXfalse$$
$$aa \models Xfalse$$

Impartial Anticipation

Impartial

- Stay with $\top$ and $\bot$

Anticipatory

- Go for $\top$ or $\bot$
- Consider $XXXfalse$

$$\begin{aligned} \epsilon &\models XXXfalse \\ a &\models XXfalse \\ aa &\models Xfalse \\ aaa &\models false \end{aligned}$$

$$[\epsilon \models XXXfalse] = \begin{cases} \top & \text{if } \forall \sigma \in \Sigma^\omega : \epsilon\sigma \models XXXfalse \\ \bot & \text{if } \forall \sigma \in \Sigma^\omega : \epsilon\sigma \not\models XXXfalse \\ ? & \text{else} \end{cases}$$

Presentation outline

Predictive Semantics

Consider the program to monitor

LTL with Predictive Semantics

Basic idea

- finite words in RV:
  prefixes of infinite, so-far unknown words

LTL with Predictive Semantics

Basic idea

- finite words in RV:
  prefixes of infinite, so-far unknown words of our program

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A first predictive semantics for LTL over finite words

$$[u \models \varphi] = \begin{cases} \top & \text{if } \forall \sigma \in \Sigma^\omega \text{ with } u\sigma \in \mathcal{P} : u\sigma \models \varphi \\ \bot & \text{if } \forall \sigma \in \Sigma^\omega \text{ with } u\sigma \in \mathcal{P} : u\sigma \not\models \varphi \\ ? & \text{else} \end{cases}$$

Too much. . .

Answers model checking question!

$$[\epsilon \models \varphi] = \begin{cases} \top & \text{if } \forall \sigma \in \Sigma^{\omega} \text{ with } \sigma \in \mathcal{P} : \epsilon\sigma \models \varphi \\ \bot & \text{if } \forall \sigma \in \Sigma^{\omega} \text{ with } \sigma \in \mathcal{P} : \epsilon\sigma \not\models \varphi \\ ? & \text{else} \end{cases}$$

More reasonable. . .

Use abstraction

- Use overabstraction of $\hat{\mathcal{P}}$
- with $L(\mathcal{P}) \subseteq L(\hat{\mathcal{P}}) \subseteq \Sigma^\omega$

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A general predictive semantics

$$[u \models \varphi] = \begin{cases} \top & \text{if } \forall \sigma \in \Sigma^\omega \text{ with } u\sigma \in \hat{\mathcal{P}} : u\sigma \models \varphi \\ \bot & \text{if } \forall \sigma \in \Sigma^\omega \text{ with } u\sigma \in \hat{\mathcal{P}} : u\sigma \not\models \varphi \\ ? & \text{else} \end{cases}$$

But . . .

How to get $\hat{\mathcal{P}}$?

- here, use simple analysis of $\mathcal{P}$
- find for $\mathcal{P}$ sequential executions of actions over φ's alphabet
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Predictive semantics

$$[w \models^R \varphi] = \begin{cases} \top & \text{if } \forall v \in R\, \forall \sigma \in \Sigma^\omega : uv\sigma \models \varphi \\ \bot & \text{if } \forall v \in R\, \forall \sigma \in \Sigma^\omega : uv\sigma \not\models \varphi \\ ? & \text{else} \end{cases}$$

Well . . .

Really. . .

- find sequences av in $\mathcal{P}$
- send av to monitor rather than only a

Presentation outline

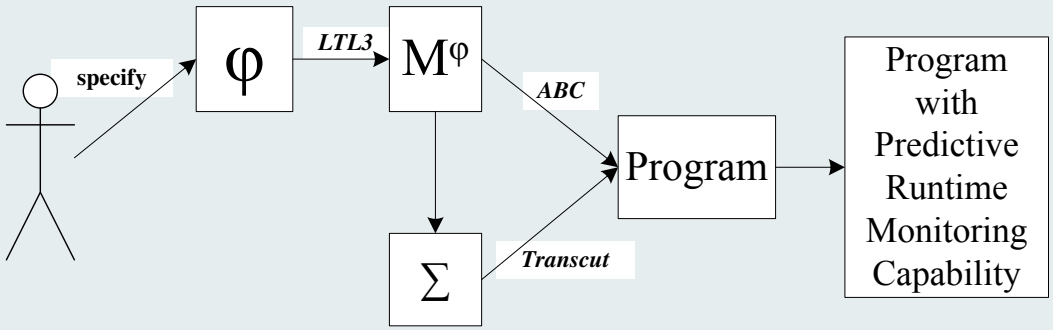
Implementation

Instrumentation

- use of AspectJ (*abc*) to obtain events from program
- analysis of strong regions, CFG and PDG to find sequential executions
- use *Transcut* to inject predictive words

Implementation

A typical usage scenario of our prototype tool



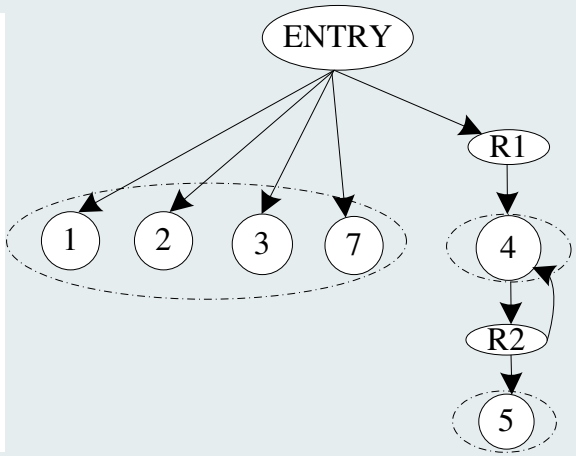
Implementation

Property

$G(\texttt{create} \rightarrow G(\texttt{update} \rightarrow \neg F(\texttt{next})))$

Strong Regions and PDG

```
1 Vector v = new Vector(col)
2 Iterator it = v.iterator( );
3 v.add(object);
4 for(each element in col){
5     process each element ;
6 }
7 it.next();
```



Experimental Results

Setup

- used Dacapo benchmarks

Results

	antlr	eclipse	fop	hsqldb	bloat	lucene
class number	224	344	967	385	263	311
method number	2972	3978	6889	5859	3986	3013
predictable shadow ratio	0% (0/23)	7.92% (53/391)	24.65% (83/288)	28.23% (45/124)	17.06% (608/1495)	25% (61/224)
predictable region ratio	0% (0/23)	3.33% (22/360)	7.86% (24/229)	11.83% (14/93)	7.88% (204/1091)	7.3% (15/178)

Presentation outline

That's it!

Thanks! - Questions?